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13 August 1996

## **DC-8 SCANNING LIDAR CHARACTERIZATION OF AIRCRAFT CONTRAILS AND CIRRUS CLOUDS**

Semiannual Performance Report Year 2  
SRI Project 6555

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Cooperative Agreement NCC 2-885

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## 1 BACKGROUND AND OBJECTIVE

A Subsonic Assessment (SASS) element of the overall Atmospheric Effects of Aviation Project (AEAP) was initiated by NASA to assess the atmospheric impact of subsonic aircraft. As part of a competitive program described by the NASA Research Announcement NRA 94-0A-01, SRI was awarded a project to develop and test a scanning backscatter lidar for installation on the NASA DC-8 (year 1), participate in the Subsonic Aircraft: Contrail and Cloud Effects Special Study (SUCCESS) field program (year 2), and conduct a comprehensive analysis of field data (year 3).

As illustrated in Figure 1, a scanning mirror pod attached to the DC-8 aircraft provides for scanning lidar observations ahead of the DC-8 and fixed-angle upward or downward observations. The lidar system installed within the DC-8 transmits 275 mJ at  $1.06\ \mu\text{m}$  wavelength or about 130 mJ at  $1.06$  and  $0.53\ \mu\text{m}$  simultaneously. Range-resolved aerosol backscatter is displayed in real time in terms of cloud/contrail spatial distributions. The objectives of the project are given below:

- Map contrail/cloud vertical distributions ahead of DC-8
- Provide DC-8 guidance into enhanced scattering layers
- Document DC-8 flight path intersection of contrail and cloud geometries
  - *In-situ* measurement positions relative to cloud/contrail shape
  - Extension of *in-situ* measurements into the vertical (integrated contrail/cloud properties)

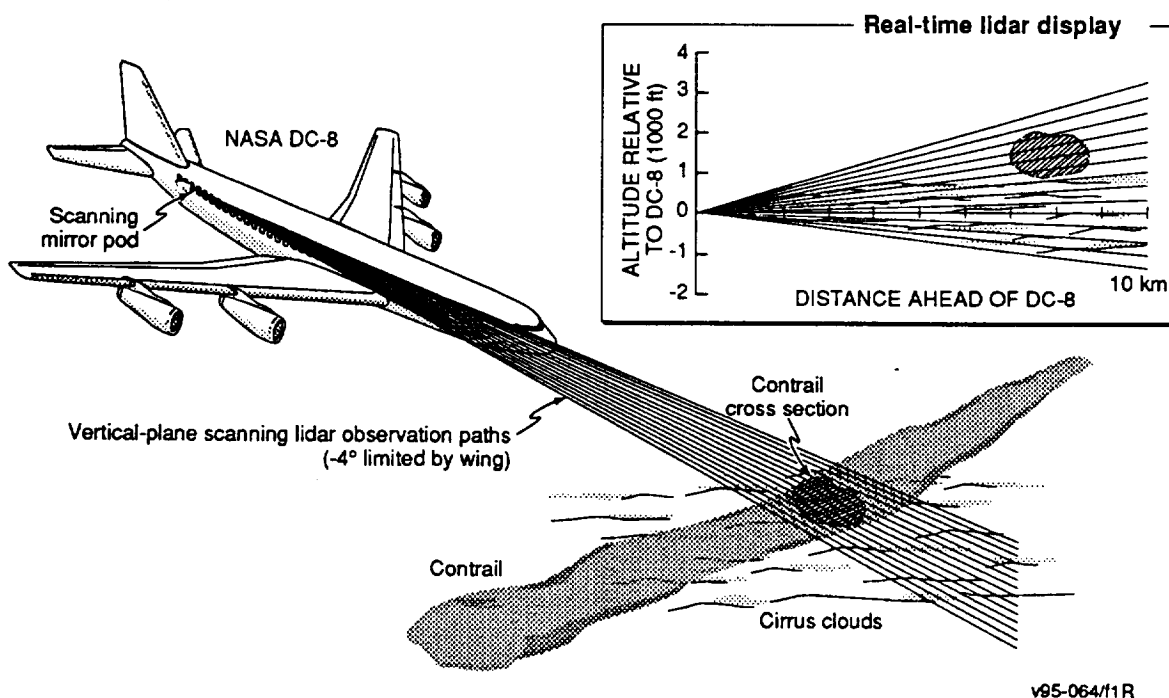


Figure 1 DC-8 SCANNING LIDAR ILLUSTRATION

- Analyze contrail/cloud radiative properties with LIRAD (combined lidar and radiometry) technique
- Evaluate mean particle sizes of aircraft emissions from two-wavelength observations
- Study contrail/cloud interactions, diffusion, and mass decay/growth
- Make observations in the near-field of aircraft engine emissions.

The scanning mirror pod may also provide a scanning capability for other remote sensing instruments.

## 2 TECHNICAL STATUS

The first half of 1996 was a very productive period for this project. Construction of the scanning mirror pod was completed and it was installed on the DC-8 aircraft. After some modification by NASA it was approved for flight testing. Other modifications to the scanner motor drive by SRI resulted in smooth scanning operation. SRI's modified ALPHA-1A aerosol backscatter lidar was installed on the DC-8. Because of the demand on DC-8 time in preparation for SUCCESS, only minimal time was given to alignment of the laser beam with the scanning mirror with alignment performed only in one direction. The lidar scanner control unit that synchronizes laser firing with the scanner mirror position and determines the next position of the mirror was programmed for a variety of fixed-angle and scan-sector operations. Figure 2 presents a picture of the scanning mirror pod attached to the DC-8 and in position for forward lidar viewing. Other details of the lidar and scanner pod are presented in a conference paper presented in this report as Appendix A.

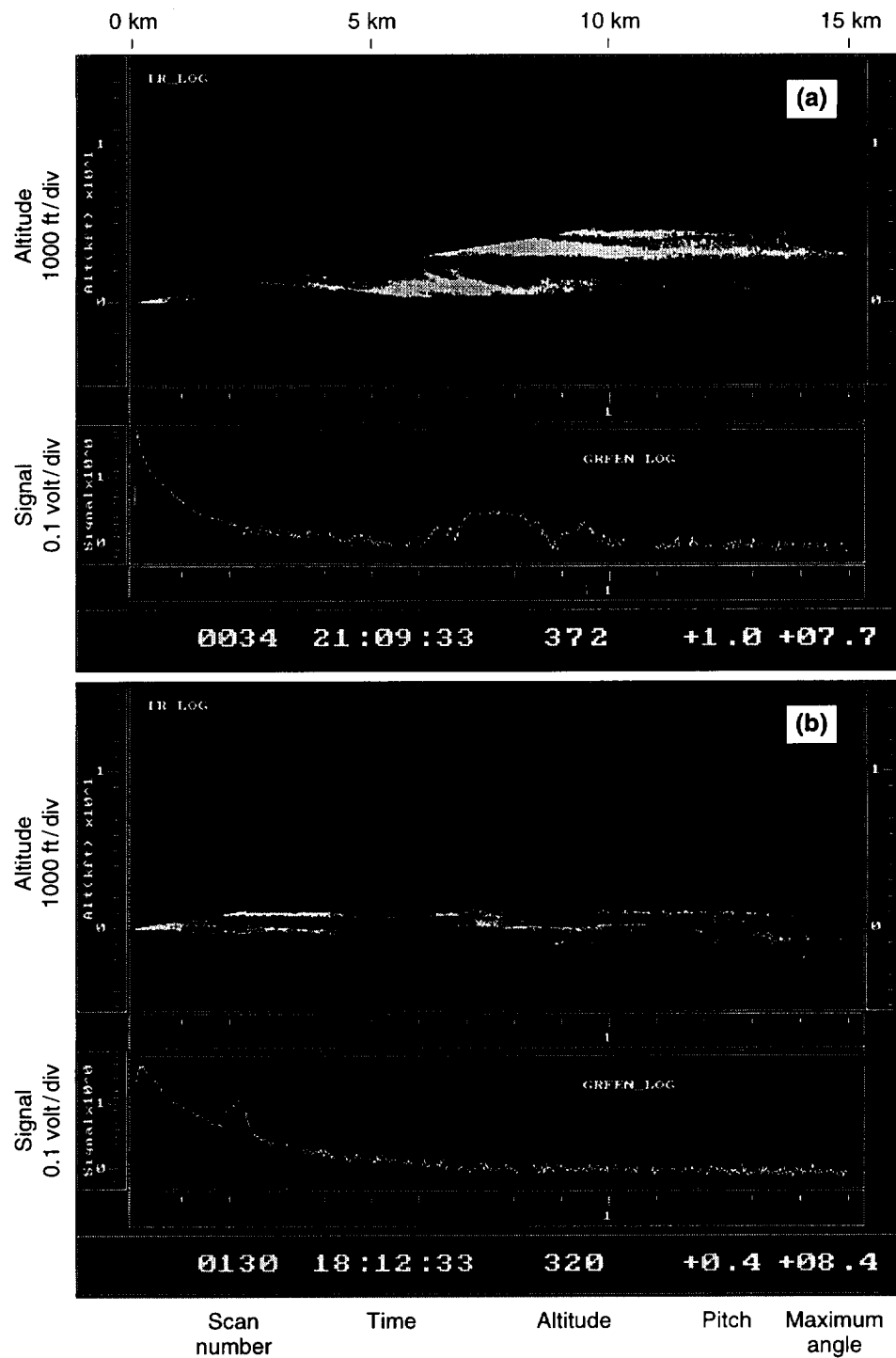
During the SUCCESS test flights and data collection flights the lidar and scanning mirror pod performed relatively well for a new sensor. An early issue was an infrequent computer failure that was difficult to isolate and seemed to occur at important lidar operation times. Each failure required about 5 min to reload the program and reinitiate the data recording tape unit. Some flights had no failures while other flights had as many as eight failures. This problem was solved about one-third of the way through the SUCCESS field program.

Two real-time intensity-modulated lidar data displays were employed—one for fixed angle viewing and the other for angular scan operation. The displays were generated for display on a flat-screen VGA computer monitor. The VGA input was also scan converted to standard TV format and was input to the DC-8 video network so that the lidar displays were available to the flight crew and other experimenters. The displays were also recorded on VCR tape by NASA (VHS) and SRI (HI-8). The displays proved useful for viewing clouds and contrails at distances greater than 3,000 ft. At distances less than 3,000 ft strong lidar backscatter signals typically caused saturation of the display. This resulted because of the inverse range-squared dependence of the lidar signature and because this effect could not be corrected in real-time operation. To solve this problem an A-scope (signal intensity as a function of range) was added to the displays. Examples of data displays for angular scan operation are presented in Figure 3. The flight crew became very proficient at interpreting the real-time lidar displays and using this information to help plan and direct aircraft operations. Several times, the lidar observed clouds above the ceiling of the DC-8 that will be important for interpreting radiation measurements. However, the lidar scanning in the forward direction was not able to map the emission plume of aircraft flown



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**Figure 2 LIDAR SCANNING MIRROR POD ATTACHED TO  
THE NASA DC-8 AIRCRAFT AND IN POSITION FOR  
FORWARD VIEWING OBSERVATIONS**



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**Figure 3 REAL-TIME DISPLAY OF DC-8 SCANNING LIDAR SYSTEM SHOWING ATMOSPHERIC INHOMOGENEITIES ABOUT TO BE PENETRATED BY THE DC-8 AND SAMPLED BY THE DC-8 SENSORS. THE AIRCRAFT ALTITUDE IN (b) AS INDICATED BY THE TEXT BOX WAS 32,000 feet MSL.**

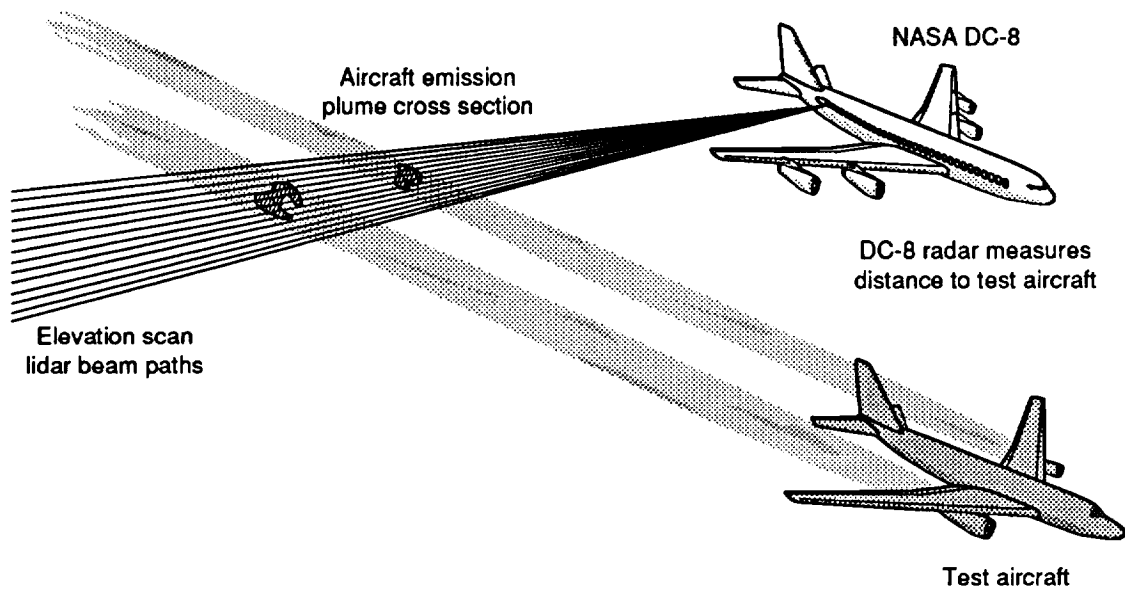
in front of the DC-8 as well as planned. Although the emissions plume was observed at all ranges from the DC-8 to the emissions aircraft, the observation along plume axis is very sensitive to fluctuations in the relative position between the aircraft. We became convinced that the best method to map the emissions plume at various distances behind the emissions aircraft with high spatial resolution is to use an elevation scanning lidar that observes perpendicular to the DC-8 and emissions aircraft in the manner illustrated in Figure 4. The test aircraft can be flown close to the DC-8 when flown alongside the DC-8 but cannot be flown close to the front of the DC-8. The scanning mirror pod can be modified for conducting such observations.

A large and complex scanning lidar database was collected. Table 1 presents an inventory of available data tapes and Table 2 presents collected data quantities. The database is made complex because of software and hardware changes made during the course of the field program as part of the effort to optimize and finalize the lidar configuration and operation. It was discovered after the field program that the DADS DC-8 pressure altitude was presented on the lidar displays while radar altitude was recorded on tape. Also, the DADS system was disconnected during a short data collection period as a means to isolate cause of the computer failures. Therefore, we plan to develop a new set of data tapes by integrating the lidar data records with the DADS data records.

In summary, the scanning lidar system was developed, installed on the DC-8 research aircraft, and successfully deployed on the SUCCESS field project. Because only minimal checkout was possible before SUCCESS, several problems needed to be solved during the field program. Nevertheless, the lidar provided real-time information on atmosphere cloud and contrail structure above, below, and ahead of the DC-8 for operational purposes, and a large database was collected that we believe will prove important during the SUCCESS analysis programs.

### 3 FUTURE PLANS

The remaining funds in the second year effort will primarily be used to attend the SASS/SUCCESS workshop to be held in October 1996 and to submit the annual report. Further data reduction and analysis tasks must wait approval of the third year project funds. The first task will be integration of DADS data records with the lidar data records and consolidating the data records into CD size files as shown in Table 2. The plan is to generate a single Exabyte tape with file sizes such that a CD of any requested data can easily be generated for transfer to other SUCCESS participants. At this time, we do not plan to generate the complete database on CD as this would require 57 CDs. Copies of the complete database can be provided on 8 mm Exabyte tape. We also plan to develop intensity-modulated displays similar to the presentation of Figure 3 for selected data. The original plan was to provide copies of the HI-8 video tape recordings of the real-time data displays to SUCCESS investigators as a means for initial viewing of data and for selection of data for case study analysis. While copies of these tapes can be provided, because of display format changes made during the field program and the early problem of close-range saturation, these displays are difficult to interpret. One solution is to regenerate video displays from the reprocessed data tapes and provide a video "picture book" as originally planned. We plan to formulate a more comprehensive data reduction and analysis plan based on research tasks defined during the October SASS/SUCCESS workshop.



ESU96-44/f1

**Figure 4 GEOMETRY FOR HIGH-RESOLUTION LIDAR**

**Table 1**  
**SASS/SUCCESS DC-8 SCANNING LIDAR OPERATIONS**

DATE 1996	DAY	FLIGHT	TAPE INVENTORY			RECEIVER BEAMSPLITTER 60 dB/40 dB	RECEIVER WAVELENGTH 60 dB/40dB	DATA COLLECTION PROGRAM	REMARKS
			NASA VIDEO <sup>1</sup>	SRI VIDEO <sup>2</sup>	SRI DATA <sup>3</sup>				
4/10	101	960201	0	1	2	90%/10%	IR/G	GO1	G and IR radar plots: fixed angle vertical in km, horizontal in time/scan vertical in 1000 ft, horizontal in time.
4/13	104	960202	1	1	3	90%/10%	IR/G	GO1	
4/15	106	960203	1	1	1	90%/10%	IR/G	GO1	
4/16	107	960204	1	2	3	90%/10%	IR/G, IR/IR	GO1	IR/IR > 1530 Z.
4/18	109	960205	1	1	2	90%/10%	IR/G	GO1	
4/20	111	960206	1	3	6	Dichroic	IR/G	GO1	5 Hz lidar rate tested (1352-1426 Z).
4/21	112	960207	2	1	10	Dichroic	IR/G	GO3/GO2	GO3 and GO2 did not fix computer problem GO3 introduced missed shots problem/DADS not recorded on some data.
4/24	115	960208	2	3	8	Dichroic	IR/G	GO3	
4/27	118	960209	2	3	1	Dichroic	IR/G	GO16	New IR receiver installed/computer failure problem fixed. New plots 5000 ft interval A-scope, 5000 ft interval fixed angle.
4/29	120	960210	2	3	1	Dichroic	IR/G	GO17	Varied dBV on plots.
4/30	121	960211	2	2	3	Dichroic	IR/G	GO17	Adjusted G(40 dB) detector gains. Changed recording ranges requiring tape changes.
5/2	123	960212	2	1	1	Dichroic	IR/G	GO17	
5/3	124	960213	1	2	1	Dichroic	IR/G, IR/IR	GO17	
5/4	125	960214	1	2	1	90%/10%	IR/IR, IR/G	GO17	IR/IR to 1737 Z, IR/G to 1858 Z, IR/IR.
5/7	128	960215	1	0	1	90%/10%	IR/IR	GO17	Only few minutes of operation allowed.
5/8	129	960216	1	2	1	90%/10%	IR/IR	GO17	Receiver calibration.
5/10	131	960217	1	1	1	90%/10%	IR/IR	GO17	Changed grayscale setting to better view high-altitude layer (above DC-8 ceiling).
5/12	133	960218	1	2	1	90%/10%	IR/IR	GO17	
5/15	136	960219	1	2	1	90%/10%	IR/IR	GO17	Adjusted 40 dB detector gains depending on signal strength.

<sup>1</sup>VCR/VHS      <sup>2</sup>VCR/HI-8 mm      <sup>3</sup>8 mm Exabyte



**Table 2**  
**DATA TAPE SUMMARY**

<b>Date</b>	<b>File Base Name</b>	<b>Tape Number</b>	<b>Total Number of Shots</b>	<b>Data Size (MB)</b>	<b>CD Number</b>
10 April 1996	96101	1	22,992	533.13	1
		2	508	11.77	1
13 April 1996	96104	1	17,358	389.12	2
		2	10,296	230.81	2
15 April 1996	96106	1	13,593	197.33	3
16 April 1996	96107	1	21,094	505.37	4
		2	13,986	335.08	5
		3	12,044	288.55	5
18 April 1996	96109	1	38,292	917.41	6,7
		2	14,168	339.44	8
20 April 1996	96111	1	27,373	761.27	9,10
		2	1,230	29.94	10
		3	18,964	461.65	11
		4	8,296	185.97	12
		5	6,384	143.11	12
		6	18,776	351.43	13
21 April 1996	96112	1	15,638	350.56	14
		2	168	3.77	14
		3	3,422	76.71	14
		4	4,478	100.38	14
		5	6,566	147.19	15
		6	7,118	159.57	15
		7	11,238	251.92	15
		8	2,230	69.32	16
		9	2,230	69.32	16
		10	5,276	118.27	16
24 April 1996	96115	1	5,612	112.92	17
		2	8,264	166.28	17
		3	8,816	177.38	17
		4	1,662	33.44	17
		5	5,872	118.15	17
		6	10,486	210.99	18
		7	4,326	87.04	18
		8	13,212	265.83	18
27 April 1996	96118	1	112,072	2,729.29	19,20,21,22,23
29 April 1996	96120	1	11,410	101.20	24
30 April 1996	96121	1	12,367	569.42	25
		2	32,255	869.91	26,27
		3	86,442	1,490.80	28,29,30
2 May 1996	96123	1	44,806	940.32	31,32
3 May 1996	96124	1	38,789	1,284.07	33,34
4 May 1996	96125	1	67,705	2,104.68	35,36,37,38
7 May 1996	96128	1	1,226	38.11	39
8 May 1996	96129	1	116,054	3,607.65	40,41,42,43,44,45
10 May 1996	96131	1	50,817	1,579.70	46,47,48
12 May 1996	96133	1	73,169	2,274.53	49,50,51,52
15 May 1996	96136	1	90,555	2,814.99	53,54,55,56,57
<b>Totals</b>			<b>1,099,635</b>	<b>28,605.09</b>	<b>57</b>

#### **4 PUBLICATIONS/PRESENTATIONS**

1. Nielsen, N.B., E.E. Uthe, R.D. Kaiser, M.A. Tucker, J.E. Baloun, and J.G. Gorordo, 1996: "NASA DC-8 Airborne Scanning Lidar Sensor Development," Proceedings of the Second International Airborne Remote Sensing Conference and Exhibition, San Francisco, California, 24–27 June 1996. Proceedings available from Environmental Research Institute of Michigan (ERIM), Ann Arbor, MI.
2. Nielsen, N.B., and E.E. Uthe, 1996: "NASA DC-8 Airborne Scanning Lidar System," Proceedings of the 18th International Laser Radar Conference, 22–26 July 1996, Berlin, Germany.
3. We have been interviewed by a reporter from Aviation Weekly and Space Technology for an article to appear in an early August issue.

#### **5 FINANCIAL STATUS**

As of 31 July 1996, approximately \$322,000 of the year one and year two funds (\$334,610) had been expended. The DC-8 installation and SUCCESS field program cost more than originally anticipated. Also, as explained above, the database is more complex than planned. Therefore the data reduction and analysis tasks must wait award of the third-year funds. The remaining first two year funds will be used to attend the SASS/SUCCESS meeting in Boulder, Colorado, 23–25 October 1996, and to submit the annual report.

## **APPENDIX A**

### **NASA DC -8 AIRBORNE SCANNING LIDAR SENSOR DEVELOPMENT\***

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\* Proceedings of the Second International Airborne Remote Sensing Conference and Exhibition, San Francisco, California, 24-27 June 1996. Available from Environmental Research Institute of Michigan (ERIM), Ann Arbor, Michigan.

## NASA DC-8 Airborne Scanning Lidar Sensor Development\*

Norman B. Nielsen, Edward E. Uthe, Robert D. Kaiser  
SRI International, Menlo Park, California 94025 USA

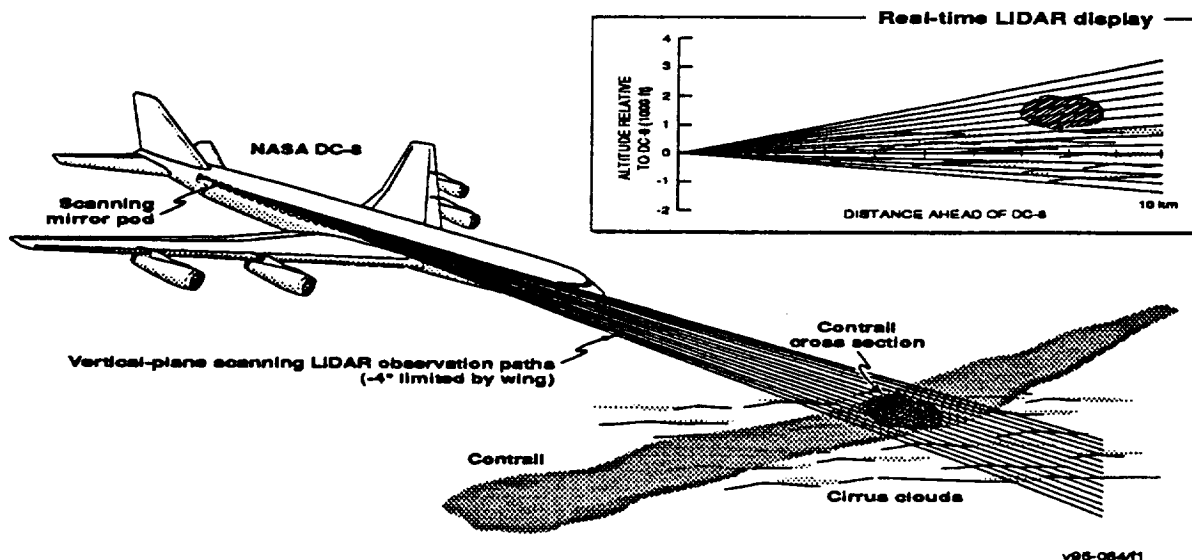
Michael A. Tucker, James E. Baloun, Javier G. Gorordo  
Raytheon Aerospace Company, Moffett Field, California 94035 USA

### ABSTRACT

The NASA DC-8 aircraft is used to support a variety of *in-situ* and remote sensors for conducting environmental measurements over global regions. As part of the atmospheric effects of aviation program (AEAP) the DC-8 is scheduled to conduct atmospheric aerosol and gas chemistry and radiation measurements of subsonic aircraft contrails and cirrus clouds. A scanning lidar system is being developed for installation on the DC-8 to support and extend the domain of the AEAP measurements. Design and objectives of the DC-8 scanning lidar are presented.

### 1.0 INTRODUCTION

The atmospheric effects of subsonic and supersonic aircraft fleets need better definition before substantial budgets are approved for development of advanced aircraft and their operational scenarios. As part of the atmospheric effects of aviation project (AEAP), NASA has formulated an extensive field program termed the subsonic aircraft: contrail and cloud effects special study (SUCCESS) to be conducted during April and May 1996 with flights of multiple aircraft over the clouds and radiation testbed (CART) site operated by the Department of Energy. One of the aircraft will be the NASA DC-8 with installation of state-of-the-art atmospheric chemistry sensors. SRI International (SRI) and Raytheon Aerospace Company are developing a DC-8 scanning lidar that can be operated with pointing angles of vertical upward to forward to vertical downward so that angular sectors can be observed as illustrated in Figure 1.



\*To be presented at the Second International Airborne Remote Sensing Conference and Exhibition, San Francisco, California, 24-27 June 1996.

The objectives of the DC-8 scanning lidar are listed below:

- Map contrail/cloud vertical distributions ahead of the DC-8
- Provide DC-8 guidance into enhanced scattering layers
- Document DC-8 flight path intersection of contrail and cloud geometries
  - *In-situ* measurement positions relative to cloud/contrail shapes
  - Extension of *in-situ* measurements into the vertical (integrated contrail/cloud properties)
- Analyze contrail/cloud radiative properties with LIRAD (combined lidar and radiometry) technique
- Evaluate mean particle sizes of aircraft emissions from two-wavelength lidar observations
- Study contrail/cloud interactions, diffusion, and mass decay/growth.

Design details of the lidar are presented in the following sections of this paper.

## 2.0 LIDAR SYSTEM

The DC-8 scanning lidar system comprises four major modules: laser transmitter, telescope receiver, data acquisition system, and scanning mirror pod. The first three modules are integrated into a standard DC-8 aircraft equipment rack. The telescope and laser are mounted on top of the rack with the receiver field of view and laser beam coaxial and directed through an aircraft side window port into the scanning mirror pod attached to the outside DC-8 fuselage.

### 2.1 TRANSMITTER

A block diagram showing lidar components is illustrated in Figure 2. The laser is a Spectra Physics model DCR-11 ND:YAG with a second harmonic frequency doubler. The laser runs at 10 Hz with approximately 130 mJ at both of the two wavelengths (1064 nm and 532 nm). The laser power supply and heat exchanger are contained in a separate package mounted directly to the seat rails. The flash lamp and Q-switch trigger pulses are supplied from a custom lidar program control unit. The pulses are synchronized to 60 Hz line frequency to avoid possible ground loop interferences.

### 2.2 RECEIVER

The lidar telescope has a 35 cm aperture with a Cassegrain configuration. Backscattered light from atmospheric aerosols is collected by the telescope and divided into two channels with a dichoric beam splitter. After passing through narrow band interference filters to reduce background light levels, the light from each channel is focused onto a solid state detector. On Channel 1 the 1064 nm detector (3 mm diameter) is enhanced for this wavelength and used in combination with a 60 dB logarithmic amplifier to obtain a large operating dynamic range. Data collected on this channel is primarily for short-range observation while flying directly through cirrus clouds and aircraft contrails. Channel 2 can be used for either the 1064 nm or 532 nm wavelength depending on receiver optical elements. The percentage of energy in each channel can be controlled by the beam splitter. The detector on Channel 2 is smaller in size (0.8 mm) and has more gain and radiant responsivity. This high sensitivity channel uses a 40 dB logarithmic amplifier and is used for long-range observation of sub-visible clouds. In addition to the data from the two logarithmic channels, linear data from each channel can be digitized and recorded. For



special experiments a polarizer can be added to the 1064 nm channel to differentiate between crystal structure of cirrus clouds and aircraft contrails.

## 2.3 DATA SYSTEM

The lidar data acquisition system is based on an IBM PC. Up to four channels of data can be processed, using Gage Applied Sciences digitizers, and recorded on Exabyte tape. The two linear channels use 12-bit 30 MHz digitizers and the two logarithmic amplifier channels use 8-bit 50 MHz digitizers. A low-speed 8 channel 12-bit A-D card is available for processing signals from associated meteorological sensors such as a narrow-beam radiometer. The DC-8 aircraft flight parameters and related environmental data available on a NASA supplied data network is input to the lidar data system for recording and presentation on the lidar displays.

A program control unit controls the stepping motor drive of the scanning mirror, and synchronizes it with the laser firing and data acquisition. The motor position is read by the lidar computer and added to the recorded data array. The lidar data are processed and displayed as color modulated pictorial displays in real time, on a flat panel VGA color monitor, and also a monitor at the DC-8 Mission Manager station. The video signal passes through a scan converter and is recorded on a HI-8 VCR (>400 line resolution) so that it may be analyzed on standard television receivers.

## 2.4 LIDAR SCANNER

A design study was conducted at NASA Ames using a preliminary scanning mirror concept and optical specifications provided by SRI. The design study identified the structural, aerodynamic, and system requirements to balance the performance needs of the lidar, while ensuring the scanner pod to be airworthy. Because *in-situ* sampling ports needed installation in the front sections of the DC-8, the lidar scanner was designed for installation in the rear section of the aircraft and makes use of one of the DC-8's side-viewing window ports.

A pressurized scanner pod was developed that consists of a large flat 45° diagonal mirror and an optical window mounted on a bearing assembly that is installed outside the aircraft in a cylindrical configuration as illustrated in Figure 3. Pressurization at the pod surfaces eliminates the need for a window at the DC-8 fuselage surface and reduces the total number of optical surfaces interacting with laser pulses. The pod is motor-driven and computer-controlled for positioning or scanning. It can be used in either a forward, upward, or downward viewing configuration. The pod can be locked into any desired position with a pair of opposing cam clamps. Adjustable mechanical stops limit scanning of the pod from intersecting the wing area of the aircraft. An indexed template marked in degrees indicates the pointing position of the scanner. A fairing was designed, as illustrated in Figure 4, with the assistance of NASA aerodynamicists to provide a smooth air flow around the scanner pod. The fairing is mounted to the side of the aircraft behind the scanner using two unused window ports to provide the attachment mounting support.

The scanner provides a 35 cm aperture for the lidar telescope receiver and will accommodate other SRI lidar systems. The front surface diagonal mirror is designed to be 1/8 wave flat. This helps maintain the astronomical quality of the telescope and allow focusing of backscattered light onto millimeter-sized diameter optical detectors. In the center of the large diagonal mirror is an additional laser transmitter mirror that allows the lidar to be operated in a coaxial configuration. The high energy transmitter mirror is 2 in. in diameter and can be changed to accommodate other wavelength lidar systems. The pressurized optical window of the pod (following the 45° mirror) is made of BK-7 glass, 17 in. in diameter, and 1-1/4 in. thick. It has a high energy anti-reflection coating on both surfaces to aid transmission and minimize

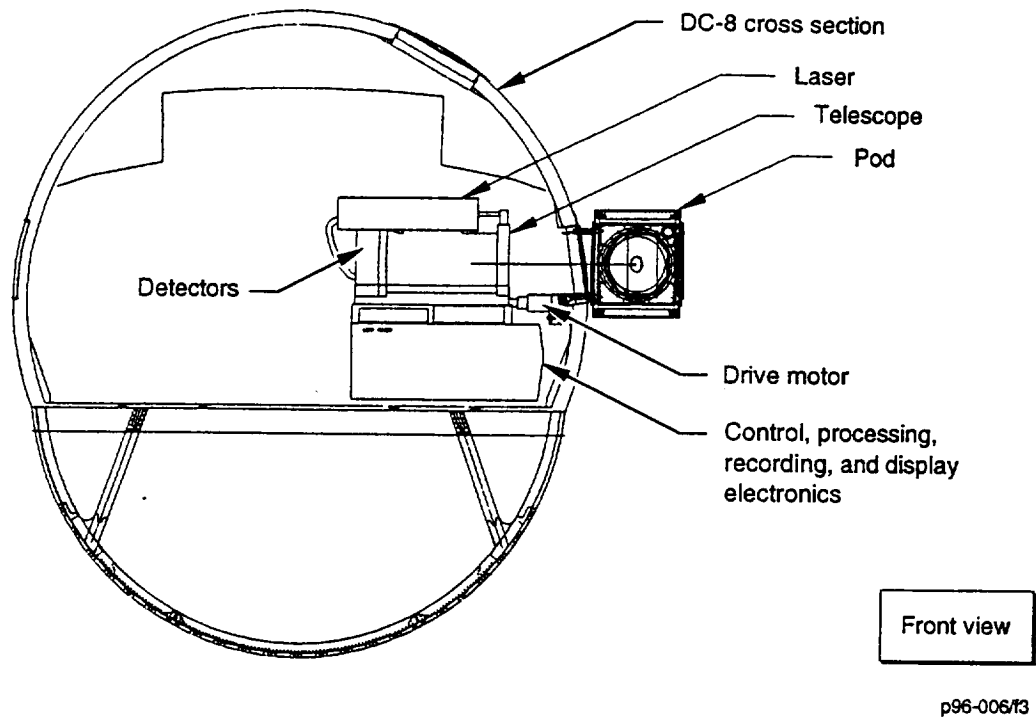


Figure 3. SRI Scanning Lidar Installation NASA Ames DC-8

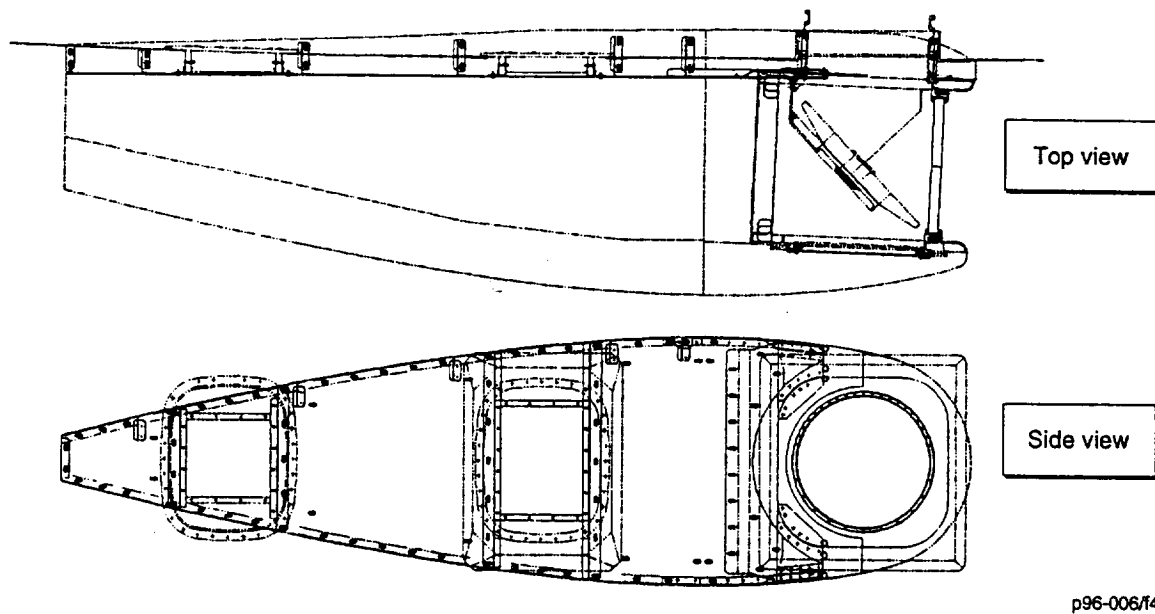


Figure 4. DC-8 Lidar Scanning Mirror Pod and Aerodynamic Fairing



energy reflection into the telescope. During landing and takeoff the scanner pod window is pointed in the aft facing direction into the fairing for protection and for receiver calibration against a low light level background.

The complete pod system and aerodynamic fairing have been analyzed for aircraft pressurization and aerodynamic loads and airworthy tests are in process.

### **3.0 CONCLUSIONS**

An airborne scanning lidar has been developed for installation on the NASA DC-8 to support atmospheric chemistry and radiation measurements. At the time of this writing, the lidar was being integrated on the DC-8 in preparation for a study of aircraft contrails and cirrus clouds related to atmospheric effects of aviation. Data collection is scheduled during April/May 1996 and, therefore, lidar data examples should be available for presentation at the conference.

### **4.0 ACKNOWLEDGMENTS**

The design, construction, and application of the scanning lidar system to atmospheric measurements is sponsored under NASA Ames Research Center Cooperative Agreement NCC 2-885.

